



Morphological and Physico-Chemical Soil Properties of Acidic Nitisol Subjected to Long-term Potato Cultivation



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Article History:

Received: 07th Jan., 2026

Accepted: 10th Mar., 2026

Published: 30th Apr., 2026

Keywords:

Acidic soils, Cation Exchange Capacity, Exchangeable Aluminum, Profile Characterization, Soil acidity, Soil Morphology

How to cite this Article:

Emmanuel R. Mwakidoshi, Catherine Muui, Esther M. Muindi, Sagar Maitra, Masina Sairam, Harun I. Gitari and Mahmoud F. Seleiman (2026). Morphological and Physico-Chemical Soil Properties of Acidic Nitisol Subjected to Long-term Potato Cultivation. *International Journal of Experimental Research and Review*, 50, 01-24.

DOI:

<https://doi.org/10.52756/ijerr.2026.v50.001>

Abstract: Soil acidity remains a critical barrier to sustainable agricultural productivity in humid and sub-humid regions, where high rainfall, intensive cultivation, and limited soil amendment practices accelerate nutrient depletion and aluminum (Al^{3+}) toxicity. Despite the importance of understanding soil acidification mechanisms, little attention has been given to the vertical and spatial variability of exchangeable acidity and its relationship with soil morphological and physicochemical properties. This study aimed to evaluate the profile distribution of exchangeable acidity and related soil morpho-physicochemical characteristics to elucidate the underlying causes of persistent acidity in cultivated agricultural landscapes. The study was undertaken in Molo, Nakuru County, Kenya, where two representative soil profiles were excavated in intensively cultivated acidic soils representing contrasting slope positions within the same agricultural landscape. The results indicated that both profiles exhibited well-developed horizonation with distinct morphological differentiation and moderate to strong structure, consistent with deeply weathered soils under high rainfall. The soils were strongly to extremely acidic (pH 4.3–5.1) throughout the profile, with acidity more pronounced in the surface and subsurface horizons. Exchangeable acidity ($\text{H}^+ + \text{Al}^{3+}$) and Al^{3+} saturation was inversely related to base cation concentration and CEC, whereas organic carbon and total nitrogen declined sharply with depth. The predominance of fine-textured, clay-rich horizons further implied advanced weathering and accumulation of low-activity clays. These findings highlight the need for targeted soil fertility management strategies emphasizing lime application, organic matter enhancement and balanced fertilization to restore cation balance and mitigate acidification. The study provides critical baseline data for designing site-specific soil amelioration and nutrient management interventions in acid-prone agricultural landscapes.

Introduction

Soil acidity is a major limitation to agricultural productivity in many humid and sub-humid regions of the world. It adversely affects soil chemical fertility,

biological activity, and nutrient availability, resulting in restricted crop growth and yield decline (Getaneh and Kidanemariam, 2016; Pramanick et al., 2021). In agricultural systems dominated by continuous cultivation



and high rainfall, acidification processes are accelerated by leaching of basic cations, accumulation of exchangeable aluminum (Al^{3+}), and the use of acid-forming fertilizers (De Azevedo and Manning, 2023; Shao et al., 2024; Hossain et al., 2023). These processes collectively deplete the soil's buffering capacity and create unfavorable conditions for acid-sensitive crops such as potato (*Solanum tuberosum* L.). The persistence of acidity across many cultivated soils underscores the need for a comprehensive understanding of its profile distribution and underlying causes (Gitari, 2018; Shao et al., 2024; Randy, 2026; Das et al., 2021a).

The development and maintenance of soil acidity are governed by the interaction of pedogenic and anthropogenic factors. Naturally, soil acidification results from prolonged weathering, mineral hydrolysis, and the leaching of base-forming cations such as Ca^{2+} , Mg^{2+} , K^+ , and Na^+ (Shetty et al., 2020; Ngaiza et al., 2025; Zhao et al., 2019; Nungula et al., 2023). Under agricultural land use, these processes are intensified by continuous cropping, nutrient mining, and fertilizer mismanagement. Over time, such activities alter the soil's chemical balance, increase exchangeable acidity, and reduce cation exchange capacity (CEC) (Gitari et al., 2019; Mwakidoshi et al., 2026; Muindi et al., 2016). In highly weathered tropical soils, these effects are often compounded by the dominance of low-activity clays and organic matter depletion, leading to poor structural stability and further nutrient loss (Santosh et al., 2024; Rahimi et al., 2023). Understanding the vertical variability of these processes is therefore essential for identifying zones of nutrient depletion and acidity accumulation within the soil profile.

Exchangeable acidity represents the acid cations maintained on soil colloids and active acidity, and the concentration of H^+ ions in the soil solution (measured as pH), which make up the two primary components of soil acidity (Getaneh and Kidanemariam, 2016). It is important because it shows how acidic the soil can get over time, especially when affected by acid rain, the leaching of basic cations like calcium and magnesium, and the continuous use of fertilizers containing ammonium (Laan et al., 2024; Mwadalul et al., 2025; De Azevedo and Manning, 2023; Shao et al., 2024). Exchangeable acidity exerts a strong, often overlooked control on nutrient dynamics in the root zone. When aluminum (Al^{3+}) and excessive hydrogen (H^+) dominate the exchange complex, essential nutrients such as phosphorus become chemically bound in forms that plants cannot use. Several authors have shown that aluminum released at low pH reacts with phosphorus to form insoluble compounds, effectively removing this key nutrient from the pool available to roots (Ileri et al., 2020).

At the same time, aluminum toxicity restricts root elongation and function, so plants are less able to access both water and nutrients even when those resources exist in the soil (Nyamaizi et al., 2022; Sande et al., 2024; Shetty et al., 2020; Jamal et al., 2025; Zhao et al., 2019). High concentrations of H^+ also displace base cations from exchange sites, contributing further to nutrient shortages and to the progressive acidification of the soil matrix (Fageria and Baligar, 2008; Mwakidoshi et al., 2023; Maitra et al., 2024). The strength of these effects depends on the soil context. Texture, organic matter content, and natural buffering agents determine how rapidly pH and nutrient availability change. Sandy soils, for example, have little buffering capacity, so small changes in exchangeable acidity may cause pronounced shifts in nutrient supply. Clay-rich soils with higher cation exchange capacity and more organic matter tend to resist abrupt pH swings and can therefore moderate the immediate impact on nutrient availability (Weil and Brady 2017; Yunan et al., 2018; Bhattacharya et al., 2023).

The accumulation of acidic cations (Al^{3+} and H^+) in the soil pool, which exchange with anions, results in a decline in soil pH, which makes the soil environment uncondusive for soil microbial activity and crop productivity (Ngugi et al., 2022). Persistent accumulation of these acidic cations without any mitigation measures results in reduced productivity, as aluminum in its soluble form disrupts the normal crop root growth and development process, hence restricting essential crop nutrient uptake (Wacker-Fester et al., 2019; Sharma et al., 2025; Fernandes et al., 2017; Psiwa et al., 2022).

Mitigation of exchangeable acidity requires an integrated approach, which will involve the use of liming agents such as calcium carbonate (CaCO_3) or magnesium carbonate (MgCO_3) and OM materials such as compost and FYM which neutralize excessive acidity by reacting with hydrogen ions in the soil and converting soluble Al^{3+} to $[\text{Al}(\text{OH})_3]$ (Kumar et al., 2021; Emmanuel et al., 2025). Adoption of such a strategy results in a reduction in soil acidity and aluminum toxicity, and significantly improves crop growth and productivity (Zhao et al., 2019; Shetty et al., 2020). Similar to lime, OM materials form part of soil OM that binds with the aluminum ions, which help in moderating soil acidity, encouraging soil microbial activity, which supports nutrient cycling, and contributes to the detoxification of aluminum in the rhizosphere (Rahimi et al., 2023; Heydarzadeh et al., 2023; Kumar et al., 2021; Sande et al., 2024). Previous studies have documented that a combination of Lime and chemical fertilizers, such as NPK, enhanced nutrient availability with increased NUE, resulting in increased yield

productivity (Ghosh et al., 2024; Ray et al., 2025b; Shadrack et al., 2020; Emmanuel et al., 2026; Sande et al., 2024; Randy et al., 2026; Sanga et al., 2024). This Integrated Nutrient Management (INM) strategy entailed a combination of organic and inorganic materials to enhance soil and crop growth and development.

Characterizing both the morphological and physico-chemical properties of soils provides a diagnostic framework for assessing the extent of acidification and its implications for soil functionality. Morphological characteristics, including horizon differentiation, color, texture, and structure, reflect pedogenic development and leaching intensity. In contrast, physico-chemical properties such as pH, organic carbon, CEC, and exchangeable bases define the soil's fertility and buffering potential. When analyzed together, these attributes provide insight into the genesis, transformation, and persistence of soil acidity, thereby guiding sustainable soil management practices and amendment strategies.

Although numerous studies have examined surface soil acidity in tropical agricultural systems, comparatively little attention has been given to its vertical distribution and association with soil morphological features across cultivated profiles. This knowledge gap limits the

understanding of acidity dynamics within the rooting zone, particularly in acid-prone soils derived from volcanic parent materials. Comprehensive profiling that integrates morphological description with analytical characterization is therefore necessary to elucidate the spatial and depth-wise variability in acidity and related soil properties.

The present study was designed to address this gap by undertaking detailed morphological and physico-chemical characterization of soils in acidic agricultural landscapes. Two representative soil profiles were described across contrasting slope positions within the same cultivated zone to capture vertical and site-specific variations. Field observations included horizon delineation, color, structure, texture, and drainage assessment, while laboratory analyses determined soil pH (H₂O and KCl), organic carbon, total nitrogen, available phosphorus, exchangeable bases (Ca²⁺, Mg²⁺, K⁺, Na⁺), exchangeable acidity (H⁺ + Al³⁺), and cation exchange capacity. The aim was to evaluate the profile distribution of exchangeable acidity and related soil morpho-physicochemical properties, and to infer the dominant factors contributing to the persistence of acidity in cultivated soils. The findings provide essential baseline information for site-specific soil fertility management and contribute to a

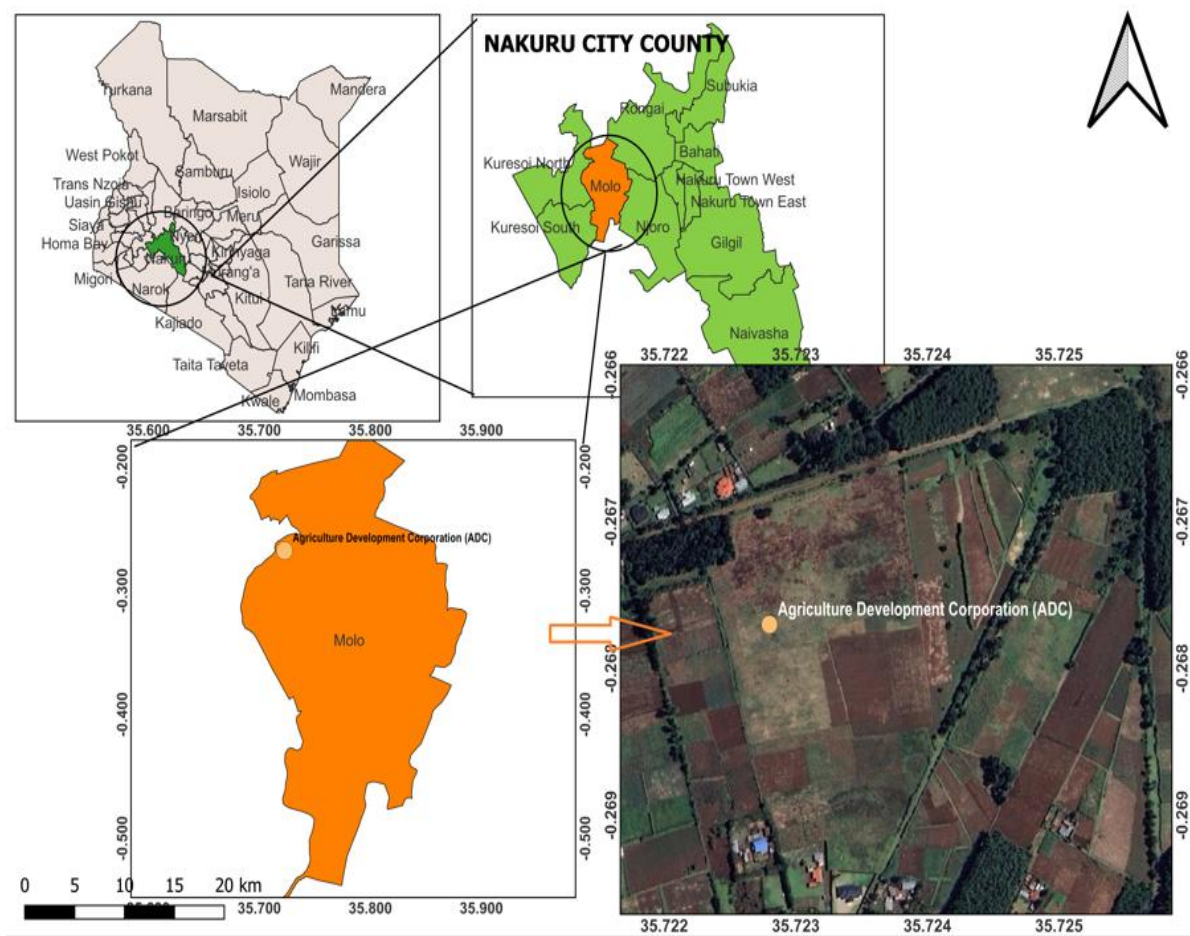


Figure 1. Map indicating Molo ADC Farm, the study location.

broader understanding of acid soil dynamics under intensive agricultural use.

These elements were essential for comprehending how the environment affected the behavior and production of soil.

Table 1. Weather and site characteristics of the representative profiles.

Profile	Weather condition	Site characteristics	Drainage condition	Native vegetation	Land use
SRK-1	Cool and humid; experiences high rainfall in the wet season and occasional dry spells.	Slope: 3%, Slope type: Straight; Position on the slope: upper middle; Elevation: 2400 m	Well-drained	<i>Cynodon dactylon</i> L., <i>Pennisetum clandestinum</i> L., <i>Bidens pilosa</i> L., <i>Podocarpus</i> spp., and other montane species	Cultivated land, primarily potato farming
SRK-2	Semi-humid; moderate rainfall with occasional dry periods	Slope: 1.5%, Slope type: Concave; Position on the slope: lower middle; Elevation: 2000 m	Moderately drained	<i>Bidens pilosa</i> L., <i>Ageratum conyzoides</i> L., and <i>Cupressus sempervirens</i> L., and predominantly grasses, with scattered shrubs.	Mixed land use; potato and vegetable farming

Materials and Methods

Site Description

The study was conducted in ADC Sirikwa farm, in Molo Sub-County, Nakuru County, located at latitude 0°16'23.1" S, longitude 35°39'33.0E, and altitude 2200 m.a.s.l., for two cropping seasons of 2024/2025 (Figure 1). It spans an area of around 100 km² and is situated about 36 kilometers from Nakuru town. The area has well-drained, extremely deep, dark reddish-brown friable clay with acid humic topsoil (humic Nitisols) (Jaetzold et al., 2010). The site forms part of a long-established potato production zone that has been cultivated for several decades under both smallholder and institutional farming systems. This sustained cropping history has contributed to the development of strongly acidic soil conditions and nutrient depletion patterns characteristic of the region's Nitisols.

During the study period, the site-specific attributes such as drainage class, natural vegetation, land use, and slope (gradient, type, position, and length) were recorded (Table 1). The representative profile's weather consisted of sporadic passing showers and scattered clouds, with average daily highs of 23°C and moderate humidity. The native vegetation, comprising the *Cynodon dactylon* L., *Pennisetum clandestinum* L., *Bidens pilosa* L., *Ageratum conyzoides* L., and *Cupressus sempervirens* L., predominated on the well-drained soil surface.

Field Methods

To choose and do site descriptions, a reconnaissance field survey was done using transect walks, auger observations, and soil descriptions in Sirikwa. This methodical technique helped identify a good site for soil analysis. Site-specific attributes, including slope gradient, erosion state, natural drainage patterns, native vegetation, and present land use, were systematically documented.

The morphological characteristics of the soil profile, which comprised soil color, texture, consistency, structure, porosity, and effective depth, were further studied. The standardized Munsell Soil Color Charts were used to determine the color of the soil, offering a dependable and repeatable system for color classification (Munsell, 1992). From the soil profile, disturbed soil samples were collected from specific genetic layers for physico-chemical analysis.

The undisturbed samples were meticulously extracted using core samplers to retain the natural arrangement of soil particles for measurements of soil physical parameters such as bulk density, saturated hydraulic conductivity, and soil water retention characteristics. Understanding soil structure, water circulation, and soil moisture retention capacity is essential for understanding plant growth and soil management techniques.

Soil Morphology Observation

The study was an exploratory descriptive investigation bolstered by data from laboratory analysis and conducted in the field through a reconnaissance survey method. Two profile pits, namely SRK-1 and SRK-2, were excavated, described, and sampled for laboratory physico-chemical analysis. The Field Observation Guidelines and Key to Soil Taxonomy (1999) were followed to observe the soil morphology in each profile. The Munsell soil color chart (Munsell, 1992) was utilized to determine the soil color in the field. To reach the groundwater or parent material, soil profiles of 1.5 meters by 1.5 meters were created perpendicular to the soil body. The morphological properties of each horizon or soil layer in the profile, such as solum thickness, border delineation, color, texture, structure, consistency, and root presence, were inspected. The gathered information was essential in determining the diagnostic horizons.

Laboratory Analysis

The Bouyoucos hydrometer method, as detailed by Bouyoucos (1936), was used to determine the particle size distribution (texture). The soil pH was measured in a 1:2.5 soil-to-water solution using a glass electrode pH meter following conventional protocols (Ryan et al., 2001). The dichromate wet oxidation method, created by Walkley and Black, was used to measure the organic carbon content (Jackson, 1967; Nelson and Sommers, 1996; Chappa et al., 2025). Available phosphorus was determined using the Olsen method, based on sodium bicarbonate extraction and subsequent measurement using a UV spectrophotometer, as outlined by Nelson and Sommers (1996), and the molybdenum blue color approach (Riley, 1962) was used to quantify it. Flame Photometry was used to determine the exchangeable bases (potassium and sodium), and the technique described by Jackson (1967) was followed to quantify the amounts of calcium and magnesium using Atomic Absorption Spectrophotometry. Micronutrients, including Fe, Cu, Zn, and Mn, were extracted using diethylenetriaminepentaacetic acid (DTPA), and their quantities were determined by Atomic Absorption Spectrophotometry, as explained by Okalebo et al. (2002). Using the method outlined by Moberg (2001), the total exchangeable bases were computed as the sum of Ca^{2+} , Mg^{2+} , Na^{+} and K^{+} . The formulas given in Equations (1–8) were used to calculate the silt/clay and C/N ratio, exchangeable sodium percentage (ESP), base saturation (BS) percentage, and nutrient ratios (K/Mg, Ca/Mg, Ca/TEB, and K/CEC%).

Silt/Clay Ratio: It was examined as an indicator of the soil's texture and its stability characteristics. The ratio of the silt to clay contents is expressed in Equation 1 (Okalebo et al., 2002).

$$\text{Silt/clay ratio} = \frac{\text{Silt content (\%)}}{\text{Clay content (\%)}} \quad (1)$$

Carbon-to-Nitrogen Ratio (C/N Ratio): The C/N ratio indicates the balance between carbon and nitrogen in soil organic matter as expressed in Equation 2 (Moberg, 2001).

$$\text{C/N ratio} = \frac{\text{Total carbon}}{\text{Total nitrogen}} \quad (2)$$

Exchangeable Sodium Percentage (ESP): ESP is used to evaluate the amount of sodium in the soil among the exchangeable cations, which affects the permeability and structure of the soil as expressed in Equation 3.

$$\text{ESP (\%)} = \frac{\text{Exchangeable sodium}}{\text{CEC}} \times 100 \quad (3)$$

Base Saturation percentage (BS): Reflects the proportion of exchangeable bases (Ca^{2+} , Mg^{2+} , K^{+} , and Na^{+}) relative to the soil's CEC as shown in Equation 4.

$$\text{BS (\%)} = \frac{\text{Total sum of exchangeable bases}}{\text{CEC}} \times 100 \quad (4)$$

Nutrient Ratios

The nutrient ratios were used to evaluate the balance and availability of key nutrients in the soil. The formulas given in Equations 5 to 8 were utilized in the computation of various nutrient rations.

K/Mg Ratio: Measured the balance between potassium and magnesium in the soil as shown in Equation 5.

$$\text{K/Mg Ratio} = \frac{\text{Exchangeable potassium}}{\text{Exchangeable magnesium}} \quad (5)$$

Ca/Mg Ratio: To evaluate the calcium to magnesium ratio as shown in Equation 6.

$$\text{Ca/Mg Ratio} = \frac{\text{Exchangeable calcium}}{\text{Exchangeable magnesium}} \quad (6)$$

Ca/TEB Ratio: The proportion of total exchangeable bases (TEB) to exchangeable calcium, as shown in Equation 7.

$$\text{Ca/TEB Ratio} = \frac{\text{Exchangeable calcium}}{\text{Total exchangeable bases}} \quad (7)$$

K/CEC (%): The percentage of CEC occupied by potassium, indicating potassium availability as expressed in Equation 8.

$$\text{K/CEC (\%)} = \frac{\text{Exchangeable potassium}}{\text{CEC}} \times 100 \quad (8)$$

Results

Soil morphological characteristics of the study site

The soils at Sirikwa were differentiated into two representative profiles, SRK-1 and SRK-2, which exhibited broadly similar morphological development but differed slightly in their fertility characteristics (Figure 2, Table 2). A thorough analysis of the soil's color, consistency, and structure shed light on the pedogenic processes affecting the development of the soil and the differentiation of the horizon in this area. Seven strata were

labeled as layers 1-7, including multiple transitional horizons and diagnostic horizons A.

Topsoil (Ap Horizon): The surface horizons of both

Eluvial Zone (Bw₁ Horizon): Moving deeper, both profiles showed the beginning of the eluvial zone in the Bw₁ horizon, the layer where leaching processes start to

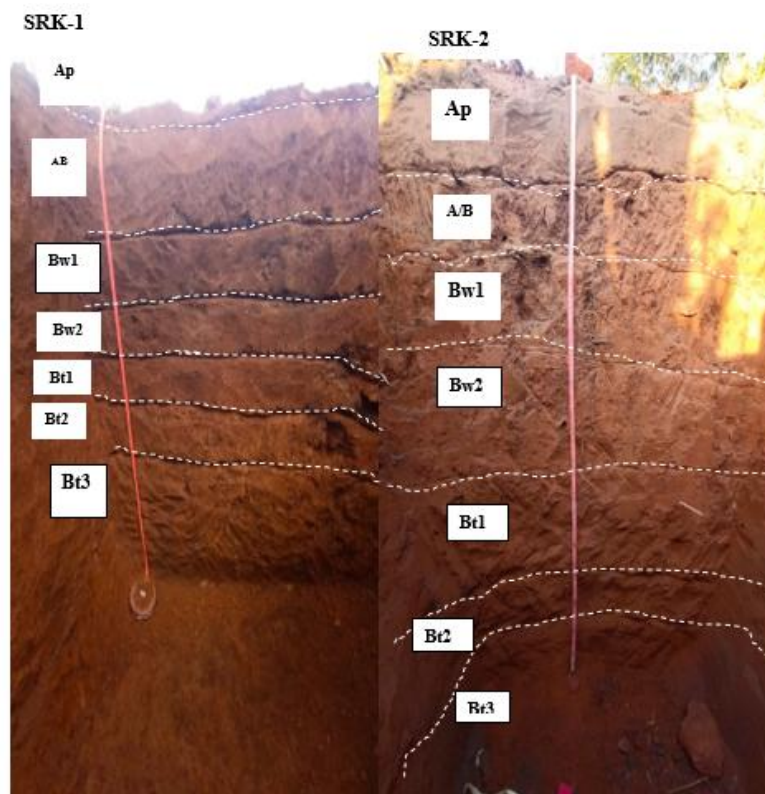


Figure 2. Soil profile from Sirikwa ADC Farm [Key: SRK-1 = Profile one, SRK-2= Profile two].

profiles exhibited a 10R 3/2 (Dark Red) hue, indicative of organic matter accumulation. In SRK-1, the Ap horizon (0–10 cm) had a granular structure and a loose consistency when dry, becoming moderately firm when wet. Its high porosity and very sticky wet consistency (due to organic matter and fine clay) indicated easy rod formation of up to 10 cm. In SRK-2, the Ap horizon (0–15 cm) exhibited similar characteristics, though it was slightly thicker. When dry, the consistency was loose, while the wet consistency was quite sticky, reflecting effective moisture retention and a high organic matter concentration.

Transition Zone (AB/A/B Horizon): In the middle layer that connects the topsoil and subsoil, I observed that the SRK-1 profile had a distinct AB horizon (10–30 cm) with a 10R 2.5/2 color, which appeared very dark red in the field. The texture here was loamier than the surface layer, and the soil felt moderately firm when moist. This zone clearly marked a transition where the organic-rich topsoil began to merge with the more mineral-dominated subsoil beneath. Rod formation extended to about 12 cm, and the soil felt sticky when wet, a sign of increased moisture retention likely linked to higher organic matter. A similar pattern appeared in the SRK-2 profile within its A/B horizon (15–25 cm), though the texture there was a bit finer and contained slightly more organic material.

modify soil composition. In SRK-1, the Bw₁ horizon (30–45 cm) maintained the same very dark red color (10R 2.5/2) and had a sub-angular blocky structure. It was fairly firm when moist, with rod formation reaching about 15 cm. The soil became moderately sticky when wet, suggesting a gradual decline in organic matter and a rise in clay accumulation. The SRK-2 profile, whose Bw₁ horizon lay between 25 and 40 cm, also displayed the same coloration but with a finer, more granular texture, hinting at slightly lower clay content in comparison.

Subsoil (Bw₂ Horizon): Further down, the Bw₂ horizon in both profiles deepened in color to 10R 3/2 (dark red), typical of layers richer in clay and iron oxides. In SRK-1 (45–60 cm), the soil developed a stronger sub-angular blocky structure, and the rods extended to nearly 20 cm. When wet, this layer was noticeably harder and stickier, which corresponded to the higher clay fraction. The SRK-2 horizon (40–55 cm) exhibited a similar red shade but with visible black specks, likely manganese oxides that pointed to the early stages of hydromorphism. Its wet consistency also felt sticky, matching the pattern of increased clay accumulation.

Illuvial Zone (Bt₁ and Bt₂ Horizons): In the illuvial section, where clay translocation becomes more evident, both profiles displayed pronounced differences from the

layers above. The SRK-1 Bt₁ horizon (60–75 cm) showed a 10R 3/3 hue (moderate red) with scattered black nodules, possibly a mix of iron and manganese oxides. The soil here was still fairly hard when moist, and rod structures stretched up to 20 cm. The Bt₂ horizon (75–90 cm) maintained the same color tone but with a denser blocky structure and an even stickier consistency, confirming heavier clay buildup. In SRK-2, the Bt₁ (55–70 cm) and Bt₂ (70–85 cm) horizons shared similar features, the same 10R 3/3 coloration, scattered black spots, and rod formation around 20 cm, indicating parallel soil-forming processes.

Bt₃ Horizon (Lower Subsoil): The deepest horizon in both profiles, Bt₃, presented a 10R 3/4 color (red) that signified declining organic matter and greater compaction. In SRK-1, the C horizon (90–120 cm) transitioned to a firm, sub-angular blocky structure with rods extending up to 20 cm. The soil here was less sticky when wet, suggesting reduced clay or a change in mineral composition. The corresponding Bt₃ layer in SRK-2 (85–100 cm) was similarly dense but contained fewer black specks, showing a weaker influence from surface processes. Its reduced stickiness was consistent with lower clay content and some mineral variation across the profile.

Table 2. Morphological characteristics of soils for SRK-1 and SRK-2 profiles at Sirikwa ADC Farm.

Profile ID	Horizon	Horizon Depth (cm)	Munsell Soil Color (Moist)	Consistency			Rod Formation (cm)	Structure	Roots	Pores	Horizon boundary
				(dry)	(moist)	(wet)					
SRK-1	Ap	0–10	10R 3/2 (Dark Red)	sh, l	fr	vst, pl	10	gr, mo, fi	ma, vf	ma, fi	c
	AB	10–30	10R 2.5/2 (Very Dark Red)	sh, l	fr	st, pl	12	gr, mo, fi	ma, fi	ma, fi	c
	Bw ₁	30–45	10R 2.5/2 (Very Dark Red)	f, l	fr	st, pl	15	sab, mo, me	co, fi	co, fi	g
	Bw ₂	45–60	10R 3/2 (Dark Red)	f, l	f	st, pl	20	sab, st, me	f, fi	f, fi	g
	Bt ₁	60–75	10R 3/3 (Moderate Red)	f, l	f	st, pl	20	bl, st, co	f, fi	f, fi	g
	Bt ₂	75–90	10R 3/3 (Moderate Red)	f, l	f	vst, pl	20	bl, st, co	f, fi	f, fi	g
	Bt ₃	90–120	10R 3/4 (Red)	fr, l	f	nst, npl	20	sab, mo, co	f, fi	f, fi	g
SRK-2	Ap	0–15	10R 3/2 (Dark Red)	sh, l	fr	vst, pl	10	gr, mo, fi	ma, vf	ma, fi	c
	A/B	15–25	10R 2.5/2 (Very Dark Red)	sh, l	fr	st, pl	12	gr, mo, fi	ma, fi	ma, fi	c
	Bw ₁	25–40	10R 2.5/2 (Very Dark Red)	f, l	fr	st, pl	15	sab, mo, me	co, fi	co, fi	g
	Bw ₂	40–55	10R 3/2 (Dark Red)	f, l	f	st, pl	20	bl, st, co	f, fi	f, fi	g
	Bt ₁	55–70	10R 3/3 (Moderate Red)	f, l	f	st, pl	20	bl, st, co	f, fi	f, fi	g
	Bt ₂	70–85	10R 3/3 (Moderate Red)	f, l	f	vst, pl	20	bl, st, co	f, fi	f, fi	g
	Bt ₃	85–100	10R 3/4 (Red)	fr, l	f	nst, npl	20	sab, mo, co	f, fi	f, fi	g

Consistence (Dry): sh = slightly hard, fr = friable, f = firm, l = loose; **Consistence (Moist):** fr = friable, f = firm; **Consistence (Wet):** st = sticky, pl = plastic, vst = very sticky, vpl = very plastic, nst = non-sticky, npl = non-plastic; **Structure:** mo = moderate, st = strong, sab = sub-angular blocky, bl = blocky, gr = granular, co = coarse, fi = fine, me = medium; **Roots:** co = common, ma = many, f = few, fi = fine, vf = very fine; **Pores:** ma = many, co = common, f = few, fi = fine, vfi = very fine; **Horizon Boundary:** c = clear, w = wavy, s = smooth, g = gradual; **Horizons:** **Ap:** Surface Horizon A with plowing or other human disturbance. **AB:** Horizon A transitioning to B, with properties of both horizons. **A/B:** Horizon shows characteristics of both A and B master horizons, with A properties dominating. **Bw:** Horizon B shows the development of color or structure, often indicating early stages of clay accumulation or leaching. **Bt:** Horizon B with significant clay accumulation (argillaceous horizon); **Bt₃:** Horizon C shows unconsolidated geological materials such as saprolite, sediments, or weathered bedrock.

The differences in soil color found in SRK-1 and SRK-2 provided information on the pedogenic processes taking place in the soil. According to Munsell (1992, the topsoil layers in both profiles were characterized by dark to very dark red hues (10R 3/2, 10R 2.5/2) that gradually changed into moderate red (10R 3/3) and then, with depth, to lighter red (10R 3/4).

In both the SRK-1 and SRK-2 profile descriptions, there was a high density of fine to very fine roots in the Ap and AB Horizons; however, the root distribution varied across the soil profile in each pit (Table 2). These horizons were distinguished by a profusion of fine roots that became noticeably shallower. There were very few fine roots found below 60 cm depth, and the number of fine roots decreased vividly from the organic-rich surface layers to the mid and subsoil horizons. The only roots found in the deeper horizons, Bt₁, Bt₂, and Bt₃, were sporadic, fine roots that mostly lined up within cracks and ped faces.

The Ap and AB horizons contained many fine to medium pores, which played an important role in soil aeration and moisture storage. These conditions generally supported root development and microbial activity, and I noticed that the distribution of soil pores closely followed the spread of the root systems. As the profile extended deeper from the Ap through AB, Bw₁ and down to the Bw₂, Bt₁ and Bt₂ horizons, the number of visible fine pores decreased noticeably. This reduction implied poorer aeration and lower porosity in the deeper layers, conditions that could restrict root growth and limit downward water movement.

The boundaries separating the horizons in both profiles varied from sharp to more gradual, showing that the soil's internal structure and composition changed unevenly with depth. In the SRK-1 profile, there was a clear and distinct shift in color and organic matter between the upper horizons, changing from dark red to very dark red across the Ap and AB layers. A slower, smoother transition

Table 3. Soil chemical properties of the representative soil profiles (SRK-1 and SRK-2).

Fertility Parameter	SRK-1								SRK-2						
	Ap	A B	B w ₁	Bw ₂	Bt ₁	Bt ₂	Bt ₃		Ap	A/ B	Bw ₁	Bw ₂	Bt ₁	Bt ₂	Bt ₃
Soil pH	4.3 0	4.6 4	5.1 3	5.32	5.53	5.7	4.98		4.4 0	4.6 0	5.20	5.40	5.5 0	5.6 5	5.00
Exchangeable acidity (meq%)	1.0 0	1.0 0	0.5 0	0.50	0.30	0.30	0.40		1.0 5	1.0 0	0.55	0.50	0.3 5	0.3 0	0.40
Total nitrogen (%)	0.4 2	0.1 6	0.3 0	0.22	0.12	0.07	0.04		0.4 0	0.1 5	0.32	0.24	0.1 3	0.0 8	0.05
Total organic carbon (%)	4.2 3	1.5 8	2.9 8	2.15	1.18	0.67	0.36		4.1 0	1.6 0	3.00	2.20	1.2 0	0.7 0	0.40
Phosphorus (Mehlich) (ppm)	42. 05	18. 45	18. 45	13.1 5	16.2	21.7	22.8		41	18. 5	18.5	14	16	22	23
Potassium (meq%)	0.9 4	0.8	0.5 6	0.44	0.48	0.46	0.48		0.9 5	0.8 1	0.58	0.46	0.5	0.4 7	0.49
Calcium (meq%)	0.4	0.6	2.4	1.8	0.4	0.2	0.2		0.4 2	0.6 2	2.5	1.85	0.4 2	0.2 5	0.22
Magnesium (meq%)	2.6 4	2.6 2	3.3 9	3.54	3.52	3.7	3.63		2.6 5	2.6 5	3.4	3.6	3.5 5	3.7 5	3.65
Manganese (meq%)	0.2 8	0.2 7	0.2 1	0.32	0.3	0.3	0.31		0.2 9	0.2 8	0.22	0.33	0.3 1	0.3 1	0.32
Copper (ppm)	1.7	1.7	1.3 5	1.00	1.35	1.35	1.70		1.7 2	1.7 2	1.36	1.05	1.3 7	1.3 7	1.72
Iron (ppm)	10 0.8 6	11 2.2 9	10 9.4 3	112. 29	92.2 9	123. 71	195. 14		10 1	11 3	110	113	93	12 5	195
Zinc (ppm)	13. 11	12. 74	8.4 8	4.21	1.66	3.73	10.6 7		13	12. 7	8.5	4.5	1.7	3.7	10.5
Sodium (meq%)	0.4 2	0.4 4	0.4 2	0.48	0.36	0.5	0.6		0.4 3	0.4 5	0.43	0.47	0.3 7	0.5 1	0.61

appeared further down, where texture and structure gradually changed between the AB, Bw₁ and Bw₂ horizons. Toward the lower sections, small black manganese nodules became more frequent, marking a visibly wavy boundary that indicated the transition between the Bw₂ and Bt₁ horizons. These nodules served as an easy field indicator of where the subsoil processes began to dominate.

The horizon boundaries for SRK-2 showed comparable patterns, with a distinct wavy boundary between the Ap and AB horizons, signifying differences in the leaching of organic matter from the surface. Similarly, the boundary between the Bw₁ and Bw₂ horizons was likewise gradual, indicating a steady accumulation of clay and iron oxides. However, there was a noticeable shift in texture and the concentration of black particles at the transition from Bw₂ to Bt₁, Bt₂, and Bt₃ horizons, suggesting hydromorphic impacts due to previous waterlogging conditions.

Soil chemical characteristics of the study Site

SRK-1 and SRK-2 soil profiles were examined for their chemical properties in seven different soil layers: Ap, AB, Bw₁, Bw₂, Bt₁, Bt₂, and Bt₃ (Table 3). The findings pointed to significant differences in soil fertility metrics that represent the profiles' nutrient availability and constraints.

values of 5.70 and 5.65. In both soil profiles, the surface horizons (Ap and AB) exhibited distinctly acidic pH values of 4.3 to 4.6 in SRK-1 and 4.4 to 4.6 in SRK-2. With increasing depth, the Bw₁ through Bt₂ horizons showed a progressive rise in pH, attaining 5.1–5.7 in SRK-1 and 5.2–5.65 in SRK-2, reflecting less acidic conditions and suggesting that acidity declined with depth. Notably, the Bt₃ horizons in both profiles reverted to lower pH values (4.98 in SRK-1 and 5.0 in SRK-2), which indicated a resurgence of acidity at depth.

The upper horizons of both profiles had a generally high exchangeable acidity; SRK-1 displayed values of 1.0 meq% in the Ap and AB layers, which were categorized as "High." Similarly, SRK-2's Ap layer had a high exchangeable acidity of 0.95 meq%. Lower exchangeable acidity was found in deeper layers of both profiles (Bt₁ and Bt₂), with values between 0.3 and 0.5 meq%, and was categorized as "Adequate" (Figure 3).

Across the two representative profiles, there were notable differences in total nitrogen levels between the layers. While deeper layers such as Bt₁ and Bt₂ displayed deficits (0.12% and 0.07%, respectively), the Ap horizon in SRK-1 had the maximum nitrogen level (0.42%,

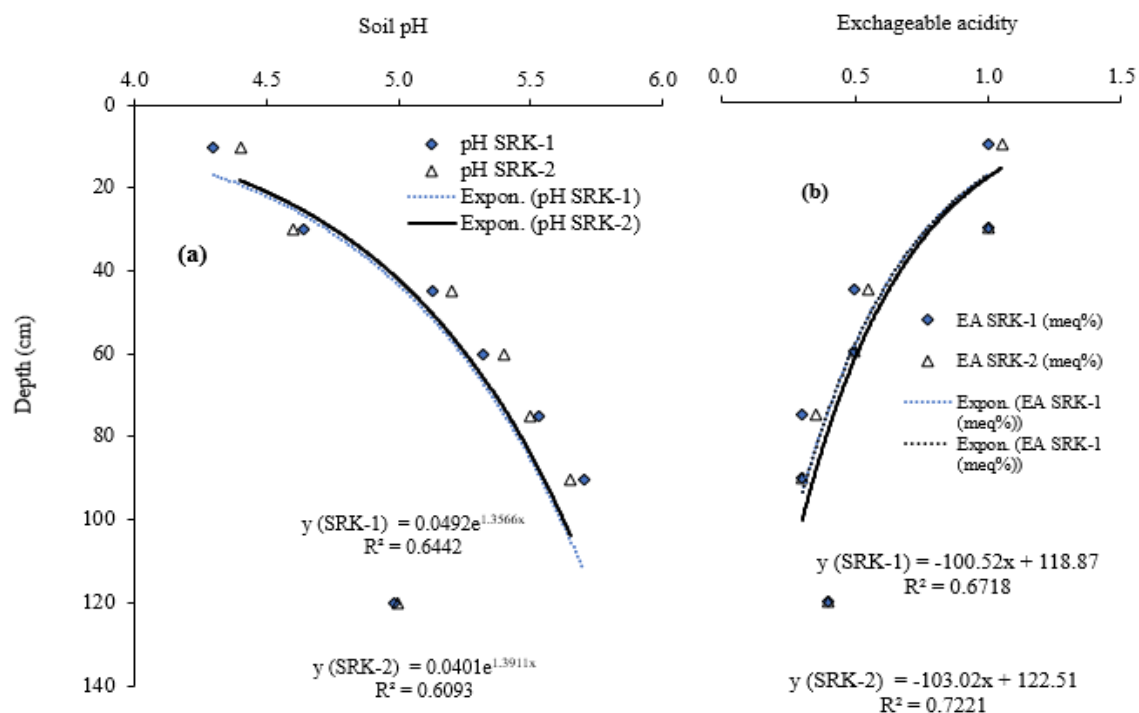


Figure 3. Distribution with depth of soil pH (a) and exchangeable acidity (b) with fitted regression models in Sirikwa soil profiles (SRK-1 and SRK-2).

For both soil profiles, the Ap horizons were more acidic (with pH values of 4.30 for SRK-1 and 4.35 for SRK-2) compared with the Bt₂ horizons, which had respective pH

categorized as "Adequate"). Similar patterns were observed in SRK-2, which had shortages in the Bt₂ and Bt₃ layers (0.06% and 0.05%) and sufficient nitrogen in the Ap layer (0.40%). In both soil profiles, organic carbon clearly

declined with increasing depth. The topmost Ap layer recorded the highest concentrations, about 4.23% in SRK-1 and 4.15% in SRK-2, values that fall within what is considered adequate for healthy topsoil. However, by the time the profile reached the Bt₃ horizon, the levels had dropped sharply to 0.36% and 0.35% in SRK-1 and SRK-2, respectively, which are regarded as deficient. This steady decline reflects how organic inputs such as crop residues and root litter mostly accumulate near the surface, where biological activity is most intense. Lower layers, in contrast, experience reduced microbial decomposition and less organic matter movement from above, explaining the low carbon values observed deeper down.

Phosphorus availability was generally low throughout both profiles. In SRK-1, the surface Ap horizon showed about 42.05 ppm, which is acceptable for potato production, but the deeper layers, such as Bw₂ and Bt₁, dropped to around 13.15 ppm. A similar trend appeared in SRK-2, where the Ap layer had roughly 40.00 ppm, falling to 12.50 ppm by the Bt₂ horizon. These results indicate that most of the plant-available phosphorus remains concentrated in the upper soil, while leaching and fixation processes limit its availability at greater depths.

Potassium levels showed a more stable pattern across depths. In both profiles, values ranged from approximately 0.94 meq% in the Ap horizon to 0.48–0.50 meq% in the Bt₂ layer, which is still considered adequate for plant growth. This suggests that potassium mobility and retention were more balanced compared to phosphorus or carbon, possibly due to the soil's clay fraction and cation exchange characteristics.

Calcium, on the other hand, was notably deficient throughout both profiles. In SRK-1, concentrations declined from about 0.40 meq% in the Ap horizon to 0.20 meq% in the Bt₃ layer, while SRK-2 ranged from 0.42 to 0.25 meq%. Such low calcium levels highlight the effects of long-term leaching and soil acidity, which tend to deplete exchangeable bases in this environment. Magnesium behaved differently: its values remained within the adequate range, increasing slightly with depth. In SRK-1, readings rose from 2.64 meq% in the Ap horizon to 3.70 meq% at Bt₂, while SRK-2 followed a similar pattern (2.60–3.75 meq%). This consistency suggests that magnesium is less affected by leaching in these soils, likely due to its stronger adsorption on clay minerals.

Across the profiles, manganese concentrations were sufficient throughout the horizons. While SRK-2 displayed higher values, ranging from 0.35 meq%, SRK-1 had values of between 0.28 meq% (Ap horizon) to 0.31

meq% (Bt₃ horizon). In every horizon, copper levels were consistently sufficient.

The Ap and Bt₃ horizons in SRK-1 reported 1.70 and 1.35 parts per million, respectively. With 1.68 ppm in the Ap horizon and 1.40 ppm in the Bt₃ horizon, SRK-2 displayed comparable levels. High levels of iron were categorized as "Adequate" across all horizons. The Fe readings for SRK-1 ranged from 195.14 ppm in the Bt₃ horizon to 100.86 ppm in the Ap horizon. The readings of SRK-2, which ranged from 98.00 ppm to 190.00 ppm, showed a similar pattern.

Zinc levels varied across the profile. The Bt₂ horizon in SRK-1 reported an inadequate level of 3.73 ppm, whereas the Ap horizon recorded 13.11 ppm ("Adequate"). Similar patterns were observed in SRK-2, which showed inadequacies in the Bt₂ horizon (3.70 ppm) and acceptable levels in the Ap horizon (12.90 ppm). Both profiles had sufficient sodium levels; for instance, SRK-1 recorded readings of between 0.42 meq% in the Ap horizon to 0.60 meq% in the C horizon. SRK-2. The levels of SRK-2 were comparable, with ranges between 0.40 and 0.58 meq%.

Nutrient ratios and percentages

Upon further assessment of the soil fertility parameters for the SRK-1 and SRK-2 profiles, it was noted that the Bt₂ layer's C/N ratio in the SRK-1 profile was 9.57, whereas that of the Ap layers was 10.07 (Table 4). The C/N ratio for the SRK-2 profile was marginally high, varying between 8.0 in the Bt₃ layer and 10.67 in the Ap layer. The measured C/N ratio values showed that both soil profiles had a moderate rate of organic matter breakdown, with deeper layers (such as the Bt₁, Bt₂, and Bt₃ layers) tending to mineralize more slowly than the surface horizons.

Base saturation measured the percentage of the soil's cation exchange capacity (CEC) that was occupied by basic cations (Ca²⁺, Mg²⁺, K⁺, and Na⁺). The Ap (100%) and Bt₂ (99.71%) horizons in SRK-1 had the highest base saturation values, while the Bw₂ (92.99%) and Bw₁ (94.87%) horizons had the lowest values. Similarly, in SRK-2, the Ap (87.84%) and A/B (92.64%) horizons had the highest base saturation, while the Bt₃ horizon had the lowest (96.27%). In the SRK-1 profile, the potassium-to-magnesium (K/Mg) ratio ranged from 0.12 in the Bw₂ horizon to 0.36 in the Ap horizon, while in SRK-2 it varied between 0.13 in the Bt₂ and Bt₃ horizons and 0.36 in the Ap layer.

Table 4. Nutrient ratios and percentages for the representative soil profiles.

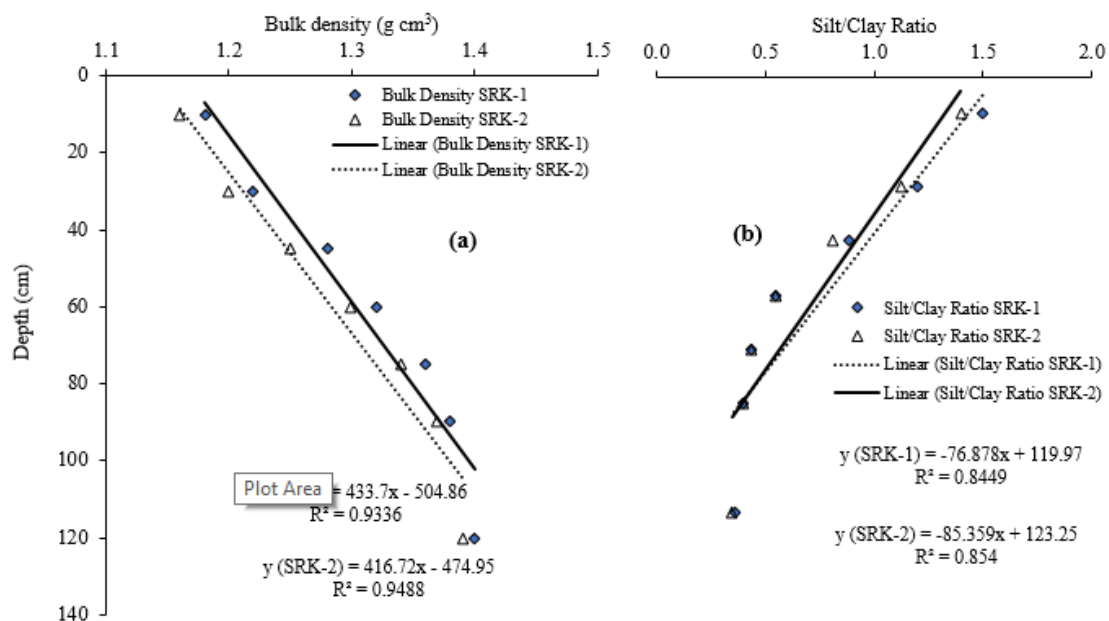
SRK-1								SRK-2						
Fertility Parameter	Ap	AB	Bw ₁	Bw ₂	Bt ₁	Bt ₂	Bt ₃	Ap	A/B	Bw ₁	Bw ₂	Bt ₁	Bt ₂	Bt ₃
C/N Ratio	10.07	9.88	9.93	9.77	9.83	9.57	9	10.25	10.67	9.38	9.17	9.23	8.75	8
ESP (%)	9.55	9.52	6.02	7.43	6.67	8.13	10.4	8.97	7.44	5.73	6.77	6.43	7.99	10.26
Base saturation (%)	100	97.67	94.87	92.99	94.44	97.69	99.71	87.84	92.64	97.47	92.56	94.74	93.32	96.27
K/Mg ratio	0.36	0.31	0.17	0.12	0.14	0.12	0.13	0.36	0.31	0.17	0.13	0.14	0.13	0.13
Ca/Mg ratio	0.15	0.23	0.71	0.51	0.11	0.05	0.06	0.16	0.23	0.73	0.51	0.12	0.07	0.06
Ca/TEB ratio	0.09	0.13	0.34	0.28	0.07	0.03	0.03	0.09	0.1	0.33	0.26	0.07	0.04	0.04
K/CEC (%)	21.36	17.32	8.01	6.77	8.89	7.47	8.27	19.79	13.39	7.77	6.67	7.89	7.85	8.24

The calcium-to-magnesium (Ca/Mg) ratio in SRK-1 was lowest in the Bt₂ horizon at 0.05 and highest in the Bw₁ horizon at 0.71, whereas SRK-2 recorded values between 0.06 in the Bt₃ horizon and 0.73 in the Bw₁ horizon. For the calcium-to-total exchangeable bases (Ca/TEB) ratio, SRK-1 showed values ranging from 0.03 in the Bt₂ and C horizons to 0.34 in the Bw₁ horizon, while SRK-2 ranged between 0.04 in the C horizon and 0.33 in the Bw₁ horizon. The potassium-to-cation exchange capacity (K/CEC) ratio followed a similar pattern in both profiles, with SRK-1 values varying from 6.77% in the Bw₂ horizon to 21.36% in the Ap horizon, and SRK-2 showing a range between 6.67% in the Bw₂ horizon and 19.79% in the Ap horizon. Across the two profiles, the Ap horizons consistently

Bulk density (BD), particle size distribution, and texture classes of SRK-1 and SRK-2 profiles

Bulk density (BD) in both SRK-1 and SRK-2 profiles increased progressively with depth, a pattern typical of structured soils under continuous pedogenic development (Figure 4; Table 5). In SRK-1, BD ranged from 1.18 g cm⁻³ in the Ap horizon (0–10 cm) to 1.40 g cm⁻³ in the deepest Bt₃ horizon (90–120 cm). Similarly, in SRK-2, BD rose from 1.16 g cm⁻³ at the surface (Ap horizon, 0–15 cm) to 1.39 g cm⁻³ at the Bt₃ horizon (85–100 cm). The relatively low surface BD in both profiles reflected higher organic matter content and better aggregation, while the increase with depth indicated compaction and reduced organic matter in subsurface layers.

Figure 4. Distribution with depth of silt/clay ratio (a) and bulk density (b) with fitted regression models in Sirikwa soil profiles (SRK-1 and SRK-2).



recorded the highest K/CEC values compared to the deeper layers, reflecting the concentration pattern of exchangeable cations along the soil depth.

The particle size distribution revealed consistent textural differentiation with depth. In SRK-1, the Ap horizon contained 50% sand, 30% silt, and 20% clay,

giving a loam texture, whereas deeper horizons transitioned to finer textures, culminating in clay (up to 50% clay in Bt₃). In SRK-2, the Ap horizon (52% sand, 28% silt, 20% clay) was also loamy, but deeper layers exhibited progressively higher clay proportions, reaching 51% in Bt₃. Such increases in clay content with depth reflected eluviation–illuviation processes, typical of Nitisols, where clay translocation and subsequent subsoil aggregation form the diagnostic nitic horizon enriched in clay.

characterized by the soft red hues, an indication of reduced OM and an increase in crystalline Fe oxides by depth. Corroboratively, these findings were consistent with the studies conducted on tropical soils, where clay illuviation and OM leaching were intimately connected to the color differences observed with depth (Mwendwa et al., 2020). Minor variances in the Munsell color chart were attributed to the microtopographic effects in the OM decomposition rates across the profiles (Mwendwa et al., 2020; Klaes et al., 2023; Hue, 2024).

Table 5. Bulk density, particle size distribution, silt/clay ratio, and USDA texture classes of SRK-1 and SRK-2 soil profiles at the study site.

Horizon	Depth (cm)	Bulk density (g cm ⁻³)	Sand (%)	Silt (%)	Clay (%)	Silt/clay ratio	USDA Texture
SRK-1							
Ap	0–10	1.18	50	30	20	1.50	Loam
AB	10–30	1.22	45	30	25	1.20	Sandy clay loam
Bw ₁	30–45	1.28	40	28	32	0.88	Clay loam
Bw ₂	45–60	1.32	38	22	40	0.55	Clay
Bt ₁	60–75	1.36	35	20	45	0.44	Clay
Bt ₂	75–90	1.38	33	19	48	0.40	Clay
Bt ₃	90–120	1.40	32	18	50	0.36	Clay
SRK-2							
Ap	0–15	1.16	52	28	20	1.40	Loam
A/B	15–25	1.20	47	28	25	1.12	Sandy clay loam
Bw ₁	25–40	1.25	42	26	32	0.81	Clay loam
Bw ₂	40–55	1.30	38	22	40	0.55	Clay
Bt ₁	55–70	1.34	35	20	45	0.44	Clay
Bt ₂	70–85	1.37	33	19	48	0.40	Clay
Bt ₃	85–100	1.39	31	18	51	0.35	Clay

The silt/clay ratio provided further evidence of textural development. In SRK-1, the ratio declined markedly from 1.50 in the Ap horizon to 0.36 in Bt₃, while in SRK-2 it decreased from 1.40 at the surface to 0.35 in Bt₃. Ratios below 1 generally indicate clay enrichment and advanced pedogenic weathering, with values approaching 0.35 reflecting strongly weathered horizons.

Discussion

Profile description and associated morphological characteristics

The major color shift changes observed in the soil matrix were a result of iron compounds, the oxidation–reduction processes coupled with differential quantities of OM (Klaes et al., 2023). Strong crimson hues in the soil were attributed to the present crystallized iron oxides, such as hematite and goethite. The presence of OM contributed to the dark red colors on the top soil (Klaes et al., 2023; Hue, 2024). The B-horizons in nitisols were

Notable dissimilarities were observed across the profiles on soil consistency in the dry, moist, and wet stages, which were consequent to soil management processes. All layers showed loose consistency when dry across the profiles, which was due to the well-developed granular to subangular blocky structures (Emmanuel et al., 2025). Corroboratively, similar studies on the nitisol's physical traits, loose consistency was determined to be perfect for seedling growth and root multiplication (Mwendwa et al., 2020; Hue, 2024).

With increasing moisture content across the profiles, fine-textured clay particles were observed to be cohesive, which resulted in the changes in soil quality from fairly firm to moderately firm (Nungula et al., 2023). In similar studies, OM and clay interactions enhanced soil cohesions, hence resulting in mild hardness when damp (Lal, 2016). Subsoil horizons (Bt₁–Bt₃) across the profiles had a higher clay content with a shrink–well activity due to their

flexibility and their characteristic sticky when wet consistencies. Corroborating study findings by Zhang et al. (2023), who observed similar consistency variations in deep tropical nitisols. Variations in stickiness across the profiles' subsoil strata determine the method of soil management practice to be adopted, as they impact root penetration and water transportation (Mwendwa et al., 2020).

Across the profiles, the soil structure was predominantly subangular blocky with disparate degrees of structural development according to horizons. Generally, tropical-formed Nitisols have a more developed subangular blocky structure in their subsoil layers due to their granular characteristics on the surface horizons (Horn and Fleige, 2011; Nungula et al., 2024), hence corroborating studies on the soil structural traits in tropical soils, which exhibit high aggregate stability and subsequently improve soil porosity and root penetration (Zhang et al., 2023).

Blocky formations in the deeper layers across the profiles had increased clay content with a possible shrink-swell behavior; linked to changes in the clay mineralogy and initial land management, as observed on the discrepancy in structures across the profiles with SRK-1 exhibiting coarser blocky units in the lower horizons in comparison to SRK-2 (Mwendwa et al., 2020; Klaes et al., 2023). These structural characteristics are vital in the identification and understanding of the soil stability as well as its compaction potential, which impacts nitisols' total productivity (Horn and Fleige, 2011; Lal, 2016).

Soil's ability and capacity to sustain water movement and plant productivity are denoted by its physical qualities of good root distribution, pore features, and horizon boundaries, which make it easier to deduce the soil's production potential (Khaleque et al., 2022).

Root distribution: Across the profiles, the topsoil exhibited high root density, which is an indication of adequate soil aeration and OM content (Dexter and Richard, 2009). Quite a few fine to extremely fine roots were observed in the Ap horizons, which was a characteristic availability of vital plant nutrients with favorable soil moisture (Emmanuely et al., 2025). In their studies, Maeght et al. (2013) corroborate these observations and deduce that fine roots are vital for adequate nutrient uptake and OM cycling. Declined presence of roots in the subsurface horizons (Bw₁ and Bw₂) was attributed to reduced oxygen availability and increased soil compaction (Gaiser et al., 2011; Perkons et al., 2014).

Soil Pores: Soil's water retention capacity and root development are adversely impacted by soil pore size, as the tiny pores in the top soils correspond with the increased

biological activity, which facilitates proper air exchange and drainage (Horn and Fleige, 2011). Notably, due to reduced abundance in pore size down the profiles, water flow and root growth were greatly restricted, hence, impacting plant health in deeper soil strata (Khaleque et al., 2022).

Several studies have deduced that nitisols exhibit a well-developed pore structure in their upper layers, hence enhancing faster water infiltration and root development (Schaeffer et al., 2013; Randy et al., 2021; Kiswara et al., 2024; Shao et al., 2023). Finer pores were an indication of less permeable soil matrices in the subsoil strata, which results in waterlogging and limited root growth (Dexter and Richard, 2009).

Horizon boundary characteristics: Characteristics of horizon boundaries vary from smooth to wavy or gradual and provide information on the soil formation processes and their development. The smooth and distinctive boundaries in the Ap and AB horizons showed consistent changes in the soil structure and textural alterations, which were an exhibition of well-developed profiles (Emmanuely et al., 2024). Minor textural differences in OM concentration showed variegated characteristics in the transition zone due to the presence of distinct wavy boundaries between the Bw₁ and Bw₂ horizons (Mills and Fey, 2004).

According to Emmanuely et al. (2024) in their studies, it was deduced that the formation of wavy and irregular boundaries is a result of bioturbation, which amalgamates the soil elements and produces distinct structural qualities. Comparably, smooth boundaries exhibit clear layering and little disruption, which could be a consequence of different parent material deposition processes (Schaeffer et al., 2013).

Additionally, extremely acidic soils harbor hazardous Mn and Al, which obstruct plant root development and lower nutrient availability to crops, especially P, which is fixated in acidic environments (Li et al., 2018; Kihara et al., 2020; Singh et al., 2025). Liming has been established as a fundamental methodology to improve nutrient availability to crops and improve soil fertility by restoring ideal soil pH levels (Li et al., 2018; Onyuka et al., 2025), hence restoring vital plant nutrients (NPK) (Esilaba et al., 2023; Cheptoe et al., 2021).

According to Das et al. (2021b) and Emmanuely et al. (2025b), organic carbon is crucial for enhancing water holding capacity, soil structure, and nutrition provision for soil microbes; hence, the low carbon concentration in the deeper soil strata in the SRK-2 profile resulted in reduced microbial activity. Notably, these observations showed that soils relied heavily on external nutrient inputs in order

to maintain their fertility status. Addition of OM and inorganic fertilizers enhanced soil nutrient retention, increased water holding capacity, and buffered against acidification impact to crops (Yuan et al., 2020; Harraq et al., 2021).

Soil chemical characteristics

Exchangeable acidity (EA) and CEC are the markers of soil fertility, and EA was notably high as exhibited on the Ap and AB horizons across the profiles, an indication that soils were acidic. Nevertheless, in soils with high leaching potential, EA decreased with depth (Wan et al., 2014; Morrison et al., 2020). The ability of soil to retain essential cations such as Ca, Mg, and K was determined by CEC, which was comparatively low across the profiles, indicative of restricted capacity to store nutrients. This obliges a well-rounded fertilization strategy that prioritizes raising CEC through liming and organic amendments application (Li et al., 2018; Yunan et al., 2018; Rahman et al., 2018; Yuan et al., 2020).

Across profiles, both exhibited nutritional deficits such as low P concentrations with Mehlich P ranging from 115 to 42.05 ppm, suggesting most deeper soil strata were deficient in P (Gram et al., 2020; Singh et al., 2025). Soil pH had a remarkable effect on P availability to crops, and phosphoric fertilizers could be administered to lessen it and their effectiveness tracked through regular soil testing (Irer et al., 2019).

Nitrogen fertilization is necessary to enhance crop growth because nitrogen levels in the surface layers were also low, with values as low as 0.04% in SRK-2. A shortage of nitrogen significantly reduces crop production because it is essential for plant growth (Bremner, 2016). This shortage can be addressed by adding organic amendments or fertilizers high in nitrogen, especially in the surface horizons where the decomposition of organic matter is most active (Bremner, 2016).

Both SRK-1 and SRK-2 soils had low calcium levels, especially in the top and bottom layers. Ca is an essential nutrient for plant cell wall growth (Wacker-Fester et al., 2019; Jing et al., 2024) and is necessary to buffer soil pH. Photosynthetic activity and enzyme activation depended on both Ca and Mg availability, which were constantly low (Wang et al., 2020; Gogoi et al., 2023). Addressing these deficits through the application of dolomitic limestone would help alleviate these cations in the soil (Guzmán et al., 2017; Cezary and Beata, 2018; Parecido et al., 2021).

AI toxicity was a significant trait across the profiles and in the deeper soil strata (Bw₁, Bw₂, and Bt₁), and in acidic soils, AI becomes more soluble, preventing root growth and nutrient absorption by plants (Zhao et al., 2019; Shetty et al., 2020). According to Esilaba et al. (2023), liming is

an effective way to raise soil pH and reduce AI solubility and toxicity. Essentially, as AI toxicity signifies decreased crop yields, it would be essential to grow acid-sensitive crops (Li et al., 2018; Rahman et al., 2018).

Soil nutrient dynamics are determined by several fertility metrics in terms of ratios and percentages, such as the C/N ratio, Base Saturation, Exchangeable Sodium Percentage (ESP), and ion ratios such as K/Mg, Ca/Mg, Ca/TEB, and K/CEC, which provide crucial information on the soil physico-chemical properties affecting plant productivity. Essentially, the C/N ratio is a vital fertility metric responsible for mineralization of organic N in the soil, as plant nutrient availability is impacted by organic debris with high carbon comparable to N, and slowly decomposes to release N at a slower rate (Lal, 2016; Brady and Weil, 2017; Emmanuely et al., 2025a; Priyadarshani et al., 2026; Otieno et al., 2022).

C/N ratios were modest across the profiles, pointing to an unpretentious rate of OM degradation. The surface horizon (Ap) of SRK-1 had a high C/N ratio indicative of reduced OM degradation at the surface (Khaleque et al., 2022; Githumbi et al., 2026). Whilst OM management strategies like mulching improve N release, a high C/N ratio on the soil surface implied a steady supply of N (Smith et al., 2019; Wan et al., 2014; Gumo et al., 2025; Müller et al., 2016). Comparably, the deeper horizons in the second profile, SRK-2, exhibited low C/N ratios in the Bt₃ horizon, which implied that microbial activity was more prominent and accelerated N cycling (Khaleque et al., 2022). Corroboratively, this trend was observed in soils with lower levels of OM in the deeper layers, where, if left unchecked, N availability would be restricted (Wan et al., 2014; Müller et al., 2016).

High base saturation is an accompaniment of different vital base cations such as calcium (Ca²⁺), magnesium (Mg²⁺), and potassium (K⁺) that are necessary for plant growth (Linguist et al., 2022; Cezary and Beata, 2018). Adequate provision of these cations in the soil enhances soil fertility and plant nutrient uptake (Fernandes et al., 2017; Nielson et al., 2017; Mwadalu et al., 2022; Jamal et al., 2024; Raza et al., 2025) compared to low base saturation, which results in nutrient deficiencies, especially in calcium and magnesium, hence, impairing plant productivity (De Azevedo and Manning, 2023; Khatun et al., 2021).

Fertile soils with readily available cations for plant uptake are indicated by the high base saturation values found in the surface layers across the profiles (Cezary and Beata, 2018; De Azevedo and Manning, 2023). Precisely, the Ap horizon across the profiles exhibited a high base saturation indicative of nutrient buffering, which was ideal for potato productivity as they require a lot of calcium and

potassium to develop into tubers (Singh et al., 2025; Gram et al., 2020; Torabian et al., 2021; Srinivasarao et al., 2023). Variations in base saturations observed from the soil profiles being lower in the subsoils were a crucial determinant in adequate nutrient provision for the crops, and hence management of the entire soil profile would be crucial to guarantee consistent nutrient supply to plants (Yuan et al., 2020; Zhang et al., 2023).

Sustainability of plant productivity is also determined through the provision of a balanced K/Mg ratio (Ray et al., 2025a; Linqvist et al., 2022). Often, antagonistic effects result in imbalances in the K/Mg ratio as large amounts of Mg reduce K intake and result in its deficiency (Sullivan et al., 2016; Torabian et al., 2021). Across the profiles, K/Mg ratios were observed to be well and adequately balanced (Sidhu et al., 2024) for plant growth, especially at the surface horizons where tuber growth was supported by higher K availability (Wacker-Fester et al., 2019; Jadhao et al., 2021; Torabian et al., 2021). Subsequently, balanced K/Mg ratios in the soil, as observed in this study, demonstrate the soil's suitability for potato productivity (Laan et al., 2024; Kamboj et al., 2024; Shao et al., 2024).

Generally, crop productivity is usually impacted by nutritional imbalances caused by an excessively high or low ratio. While Mg is a key component of chlorophyll and is involved in the photosynthesis process, Ca is necessary for the formation of cell walls and the growth of roots (Guzmán et al., 2017; Cezary and Beata, 2018); hence, a balanced Ca/Mg ratio is crucial. Across the profiles, the Ca/Mg ratio was imbalanced in the deeper horizons, where Mg was dominant over Ca. This implies a greater concentration of Mg in the subsoil, which subjects the plants to risk for calcium insufficiency, particularly in deep-rooted crops (Jadhao et al., 2021; Krishna et al., 2024). To remedy this imbalance, liming is the best strategy to be adopted to boost Ca supply and availability to crops (Li et al., 2018; Maitra et al., 2024).

The Ca/TEB ratio indicated the soil's CEC complex had a lot of Ca, which was vital in enhancing soil physical properties (Chen et al., 2024), corroborating several studies that deduce that Ca abundance in the surface strata is advantageous in the preservation of soil fertility (De Azevedo and Manning, 2023; Li et al., 2018; Muchai et al., 2023; Khatun et al., 2021; Garbowski et al., 2022). Similarly, these findings were consistent with research showing that soils that have been treated with calcium typically have better physical characteristics, which promote healthier crop growth (Khatun et al., 2021; Esilaba et al., 2023; Golicha et al., 2026). Comparatively, a high K/CEC ratio also indicated that K occupied a sizable percentage of the soil's nutrient exchange sites, making it

easily absorbed by plants (Brady and Weil, 2017). Across the profiles, K/CEC ratios indicated that plants had adequate access to K to sustain plant growth without running the danger of nutrient imbalances (Martirosyan et al., 2024; Nasar et al., 2025; Laan et al., 2024; Shao et al., 2024).

Comprehensively, the fertility ratios provided vital information on the soil's chemical characteristics across the profiles, and these findings were corroborative with similar studies on acidic soils, which provided a thorough basis for creating soil management plans to improve fertility and maximize crop productivity (Ghosh et al., 2024; Nasar et al., 2022; Cai et al., 2018; Liu et al., 2021).

Soil physical characteristics

Across the profiles, bulk density (BD) exhibited an increase with depth, which reflected a decline in OM, root channels, and aggregation with depth, hence resulting in reduced soil porosity (USDA-NRCS, 2019). The surface values corresponded to well-aggregated loamy soil likely conducive to root growth. Deeper horizons showed higher BD, signifying compaction, which limits root penetration and water movement, yet values below the growth-limiting threshold ($\approx 1.47 \text{ g cm}^{-3}$ for clay soils) suggested subsoil can still support potato rooting (Fernandes et al., 2017).

The SRK-1 and SRK-2 profiles clearly exhibited textural stratification, with surface horizons (Ap) dominated by loam to sandy loam textures (20–30% clay), while deeper horizons progressively transitioned to clay-rich layers containing 45–51% clay. This gradient is consistent with active pedogenic processes of clay illuviation, where fine particles are eluviated from the upper layers and deposited in the B-horizons, forming the diagnostic nitic horizon that characterizes Nitisols (Emmanuel et al., 2024; Mwendwa et al., 2020). Similar clay translocation and accumulation in Kenyan highland Nitisols have been reported by Chulo et al. (2021), with subsurface horizons enriched in clay serving as a key diagnostic feature. The buildup of clay contributed to high BD while reducing soil macro-porosity, thereby restricting aeration and water infiltration, though clay-rich subsoils also enhance nutrient retention and cation exchange capacity (Emmanuel et al., 2024; Yunan et al., 2018; Mwendwa et al., 2020). The relatively coarser textures in surface layers promoted infiltration and aeration, making them more favorable for agricultural use, particularly for shallow-rooted crops like potatoes. In contrast, the deeper clayey horizons imposed barriers to drainage and root penetration, a phenomenon that constrained crop rooting depth and water use efficiency. Notably, the Bt₁ horizon of SRK-1 contained slightly higher clay content than SRK-2, pointing to localized differences in pedogenic

development and horizon differentiation, as highlighted in studies on tropical weathered soils (Hue, 2024).

The silt-to-clay ratio in both profiles declined deeply from approximately ~1.50 in Ap to ~0.35 in Bt₃. Values below the threshold of 0.4 indicated strong clay accumulation in subsoil and reflected advanced soil weathering and eluviation–illuviation processes, consistent with Nitisol development (Muindi et al., 2016). Similar ratios have been reported in Kenyan and Tanzanian highland Nitisols and serve as pedogenic markers of stable, structured soils with diagnostic Bt horizons enriched in clay (Muindi et al., 2016; Emmanuely et al., 2025b; Mwendwa et al., 2020; Hue, 2024).

High clay content and increased BD in deeper layers reduced saturated hydraulic conductivity (K_{sat}), with fewer macropores transmitting water effectively (Mwendwa et al., 2020). This constrained water infiltration and regulated moisture availability critical for potato production, as they are sensitive to both drought stress and waterlogging. Maintaining a well-structured topsoil is therefore essential to buffer against such limitations.

Collectively, the observed trends on the profiles from the loamy Ap horizon, clayey Bt horizon, low silt/clay ratio, and increasing BD, aligned with the general characteristics of Nitisols, common in tropical highlands of Kenya (Mwendwa et al., 2020). These soils typically support high crop yields due to depth, fertility, and structure, yet require careful management to preserve surface porosity and mitigate subsoil compaction.

Given the moderate surface BD and good structure in the Ap horizon, root establishment and early crop growth and development become favorable. However, the denser Bt layers may hinder deeper root penetration, particularly during dry periods. Agronomic practices such as minimal soil disturbance, organic amendments, or targeted subsoiling may help in the reduction of BD by 0.1 g cm^{-3} and have been proven to significantly improve root development and yield in similar textured soils (Sanchez, 2019; Sileshi et al., 2025; Nyamaizi et al., 2022).

Overall, both profiles showed similar pedogenic trends, with loamy surface soils underlain by progressively clayey horizons of higher bulk density and lower silt/clay ratios. These circumstances propound increased root penetration resistance with depth.

Conclusion

The study revealed that the investigated soils are predominantly deep, well-developed Nitisols with favorable physical attributes for crop growth, including stable structure, good drainage, and adequate rooting

depth. However, these soils are chemically constrained by strong to extreme acidity, elevated exchangeable aluminum, and low base saturation throughout the profile. The vertical distribution patterns indicated that exchangeable acidity, rather than soil pH alone, provides a more accurate diagnostic indicator of soil fertility decline and the persistence of acidity in cultivated systems. The high aluminum saturation and limited cation exchange capacity reflect intense leaching, nutrient mining, and inadequate replenishment of basic cations under continuous cultivation. Collectively, these findings underscore that the persistence of acidity is a result of both inherent soil properties and long-term anthropogenic pressure from unsustainable land use and fertilizer practices.

Conflicts of Interest

The authors declare no conflicts of interest to report regarding the present study.

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How to cite this Article:

Emmanuel R. Mwakidoshi, Catherine Muui, Esther M. Muindi, Sagar Maitra, Masina Sairam, Harun I. Gitari and Mahmoud F. Seleiman (2026). Morphological and Physico-Chemical Soil Properties of Acidic Nitisol Subjected to Long-term Potato Cultivation. *International Journal of Experimental Research and Review*, 50, 01-24.

DOI : <https://doi.org/10.52756/ijerr.2026.v50.001>



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